TECHNICAL NOTES

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No. 637

PRELIMINARY FATIGUE STUDIES ON ALUMINUM

ALLOY AIRCRAFT GIRDERS

By Goodyear-Zeppelin Corporation

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SUMMARY

Preliminary information on the complex subject of the fatigue strength of fabricated structural members for aircraft is presented in the test results obtained on several different types of airship girders subjected to axial tension and compression in a resonance fatigue machine. A description of this machine as well as numerous photographs of the fatigue failures are given. There is also presented an extended bibliography on the subject of fatigue strength.

GENERAL DISCUSSION OF PROBLEMS INVOLVED

It has been recognized for a great many years that loads subject to numerous variations during the life of a machine are more severe in their effect than constant loads. Scientific research on this subject of fatigue has been carried on for the last three-quarters of a century, and many general relations have been established and data collected, which are useful in our present study.

In certain respects, however, the problems of aircraft design differ decidedly from those considered in most previous investigations of this subject. These investigations have been largely concerned with the establishment of endurance limits, or stress cycles of various kinds which can be withstood an indefinite number of times. This information is suitable for the design of parts whose life history consists only of an enormous number of approximately equal stress cycles. Many machine parts have such

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*This technical note is based on an investigation of fatigue of airship girders made for the Bureau of Aeronautics, Navy Department, by the Goodyear-Zeppelin Corporation.

a life history. At the opposite extreme are parts sub-
jected to a constant load. Their design can be based on
ordinary static load tests.

In most practical cases, however, the average life
history falls somewhere between these extremes, and con-
sists of various numbers of different kinds and intensi-
ties of load cycles applied to the same member. In some
of these cases we can immediately simplify the problem,
and perhaps reclassify it in one of the above extremes, by
neglecting certain kinds of cycles: thus any number of any
kind of cycles below the endurance limit or a small num-
ber of cycles below the yield point probably can be neg-
lected. However, there is not at present any theory, or
sufficient data, for the rational analysis of most cases
of this sort.

In nonaeronautical applications this lack of knowl-
edge has not usually been considered very serious. Most
designs are frankly based on past experience with many
similar designs rather than on theoretical considerations.
Weights are usually not critical, so that one can be safe
by keeping the maximum stress cycles below the fatigue
limit even when this is not really necessary, or by using
very large factors of safety.

In aeronautical applications most of the loads which
must be considered in design are of this varying cyclical
type described. Rapid developments in design and the com-
paratively small number of units, particularly in the case
of airships, makes the information which can be gained
from past experience less complete than in other fields of
engineering. Moreover, past experience is a definite guide
only when failure takes place. Freedom from failure alone
does not reveal how close we may come to it, or how much
unnecessary weight may be wasted in oversize parts.

Since we can neither risk failure in important parts
nor carry unnecessary weight, it is evident that work in
developing more efficient methods of designing for these
complex conditions is important. There is, to be sure, no
evidence that past practice in aircraft design, which has
been based largely on the few cycles of the maximum load
to be expected during the life of a part, without much
consideration of lesser cycles, has been inadequate – that
is, that fatigue has been an appreciable factor in struc-
tural failures which have occurred in the past. It is en-
tirely possible that, if the whole truth were known, the

distribution in number and severity of the lesser stress cycles would be found such as to be completely negligible in design. It is more likely, however, that some redistribution in weight from parts unnecessarily strong to parts closer to the border line would be found beneficial. Moreover, until we know exactly how we stand on this question, we must tread somewhat carefully in considering changes in design — for instance, in taking full advantage of improvements in the static strength of girders.

A rational study of this question would involve two parts. First, we must determine, or at least get some idea as to the probable life history in respect to loads and their variations of representative parts of an aircraft in actual service. Second, we must study the effect of such stress histories on the parts concerned and, if fatigue is found to be a critical condition, study possible changes which may improve matters.

The first part, determining roughly the loads and their variations which actually occur in an aircraft's lifetime, is doubtless the most difficult, but none the less necessary if we are to get very far with the problem. Variations in the load on structural parts which run into numbers having any importance in relation to fatigue, are due principally to control maneuvers, engine and propeller vibration, and aerodynamic forces, including vibrations induced by the propeller slipstream or other unsteady air flow.

Engine and propeller vibration is usually local in its effect and presents problems similar to those in other types of power-plant mountings, with similar partial remedies in flexible engine mounts, damping, avoidance of resonance, etc. Vibration induced by the propeller slipstream is in a somewhat similar class. The probable number of such vibrations can readily be figured and is so large that it might as well be considered as infinite, but the range of such vibrations (as distinct from the average stress, which is determinable from statical considerations in the usual manner) is almost impossible to estimate theoretically. In actual aircraft it can readily be measured by short-time tests at different speeds with conventional vibrometers, and the readings translated approximately into stress.

The stresses produced by control maneuvers can be and have been studied by short-time, full-scale tests, using

ordinary strain gages. However, this is probably not im-
portant from a fatigue standpoint, because maneuvers not
due to recovery from atmospheric disturbances probably do
not occur often enough in the life of long-distance air-
craft to be important in fatigue. The effects of maneu-
vers due to atmospheric disturbances might as well be
lumped in with the effects of the disturbances themselves.

This effect of atmospheric disturbances seems to be
the big question mark for aircraft designers not only in
relation to load variations on most of the structure, but
in relation to critical load conditions as well. Theoret-
ical or wind-tunnel investigations of hypothetical gust
conditions give us a picture of the possible relative dis-
tribution of load and the relative effects of size, shape,
speed, etc., but they cannot tell us much about the abso-
lute magnitudes until we know more about the structures
and intensities of the atmospheric disturbances likely to
be actually met during an aircraft's life. We can, of
course, draw conclusions about this from the history of
aircraft, although failures are frequently obscured by
lack of knowledge, or disagreement, as to the cause, while
freedom from failure gives only a one-sided indication,
as discussed before.

It is our opinion that the only feasible way at this
stage of aircraft development, of getting more complete
information is by the installation of self-recording in-
struments in an airplane engaged in regular operation.
Such instruments should record with reasonable accuracy
all the information required for designing against either
static or fatigue failure. This information might include
the maximum and minimum stresses ever reached, and the num-
ber of cycles of several different ranges of stress, say
from 6,000 to 9,000 pounds per square inch range, 9,000 to
15,000 pounds per square inch range, etc., all stress cy-
cles being approximately weighted to allow for the known
effect of the different mean stresses corresponding to
them. The instruments should be completely automatic and
not interfere with normal operation of the aircraft. They
should be connected all the time and not require attention
more than a few times a year, when they would, of course,
be read. They must, of course, be reasonably cheap, light,
and accessible so that a number of them can be used with-
out excessive expense. An instrument to answer these re-
quirements is under development at the present time.

Objections have been raised to such strain measurements,

that they would be incomplete or useless unless coordinat-
ed in some way with each other and with manometer readings
showing the changes in aerodynamic forces which produce
the changes in the forces in the structure. However, the
taking and studying of such coordinated data would be an
enormously more expensive program than the one suggested.
In the last analysis the designer of an aircraft needs to
know the maximum forces and the force changes which will
be experienced by different parts, but he does not neces-
sarily need to know the combination of circumstances which
causes these forces.

To be sure, complete studies of completely coordinat-
ed data may be necessary before he can rationally extrapo-
late from data on certain parts of the aircraft to all
other parts, and from data on one type of aircraft to any
other type. But at the present moment the data from even
a dozen or so instruments such as proposed, placed at a
few strategically located points in typical aircraft, and
read a few times over an interval of a year or two, would
represent a large advance in our information. Such data
would, of course, be used in conjunction with our present
aerodynamical and stress-analysis knowledge, which provide
a reasonable means for extrapolation for the present.

More elaborate programs may be possible later but pro-
grams of the type proposed, using as many instruments as
seem practical, should certainly be carried out as soon as
possible. Without such information we may design very in-
efficiently as regards the effect of atmospheric disturb-
ances.

The effect of such disturbances is, of course, much
greater on some parts of an aircraft than on other parts.
It is therefore useful, both for determining the most
suitable points for attaching instruments in carrying out
the above program and for design or other purposes while
we are waiting for such a program, to roughly classify
different parts of the aircraft as to the importance of
this question.

As a result of our own contact with these problems,
we are inclined to classify the structural parts of a
rigid airship into seven groups as follows:

1. Members whose strength is mainly determined by
        consideration of a rare emergency, such as loss
        of gas cells. The frequency of occurrence of

such an emergency can probably be regarded as insignificant insofar as fatigue is concerned.

2. Members which are expected to suffer occasional high stresses due to unfortunate coincidences of unusual gusts with harsh maneuvers. The appraisal of this contingency depends much on the expected method of operation of the airship in service.

3. Members likely to be subjected to important stresses by some temporary severe condition of dynamic lift or unusual trim or loading, or in ground handling and mooring. Such stresses may occur at intervals and last for a certain while.

4. Members likely to bear the brunt of the forces incidental to flight control; these forces will occur essentially at the frequency of the elevator and rudder controls. They are greatly enhanced in rough weather or by special maneuvers, while in straight flight through calm weather this type of stress cycle is insignificant, sometimes for hours. Flying with dynamic lift or out of trim may make the cycles due to elevator movement unsymmetrical.

5. Members subjected to repeated loads by people walking or climbing over them may suffer load repetitions which can be estimated from service considerations.

6. Members exposed to the slipstream of propellers or to the vibrations transmitted from parts of the power plant and accessory machinery may suffer stress repetitions rapidly growing into millions. It is in these members where true fatigue considerations may be predominant. Here the limitation of stress amplitudes is mainly a matter of avoiding resonance, as in most instances it is relatively easy to keep nonresonance stresses low.

7. Flutter of self-sustained aerodynamic resonance of parts exposed to the wind has not yet been reported as giving serious troubles on airships. If air speeds are increased, flutter problems may demand attention also.

The second part of any program for studying this question, namely, the study of the effect on an aircraft's parts of the types of stress history they will actually experience, and possible improvements which can be made, should logically come after the first part, above. Until the first part is at least partially completed, we do not even know if fatigue is a critical condition which needs to be considered at all at present. However, since it is probable that fatigue is of some importance in at least some parts, it is undoubtedly useful to study the general fatigue resistance of present types of construction which are satisfactory statically, and means of improving the fatigue resistance without undue sacrifice in other respects.

Since the Goodyear-Zeppelin Corporation has had no opportunity to carry out a program of flight tests, its tests as well as the remaining portion of this paper are of necessity confined to studies of the fatigue resistance of airship girders.

Since a laboratory fatigue test can only simulate actual conditions in an idealizing manner, it is necessary in devising such tests to ascertain what factors may have an influence upon the number of cycles of a stress below the static strength a structure member can withstand. Some of these factors are discussed below.

One fundamental factor is the material from which the member is fabricated. A great deal of information is available on the fatigue strength of steel and strong aluminum alloys. The American strong aluminum alloy which is of primary interest in the present investigation is 17S-RT. Fatigue curves showing the results of reversed bending tests made by the Aluminum Company of America on 17ST and 17S-RT sheet are reproduced here in figure 1.

In airship construction, girders are usually designed to transmit axial forces. Some of them may be called upon to take some bending and shear. Torsion is usually insignificant. To transmit compression effectively without buckling at low stress, the boom members are generally channeled. The fabrication of these channel bends or grooves may have an influence on the fatigue strength. This problem can probably be studied sufficiently by tests on booms. Since this manipulation redistributes the stresses locked up by the last cold work done on the sheet, one may be led to assume that at convex regions where the

material has been stretched, the material would be more
susceptible to fatigue. However, it may be that such
stretching is inconsequential when it is at right angles
to the forces applied in an axial fatigue test.

In booms of composite construction in which several
elements paralleling each other are joined together by
riveting or welding, the joining elements will carry part
of the load even though their main purpose is to support
the edges against crimping or to prevent the channels from
becoming unstable in torsion or bending between lattices.
These elements may produce appreciable stress concentra-
tions or notch effects. Their seriousness must be expect-
ed to depend on the riveting or spot-welding technique and
on the rivet pattern with respect to the stress flow in
the surrounding material. In many of the past tests of
such structures the initial fatigue cracks started from
rivet holes or weld spots or at least passed through such
points. It is obviously impractical to design most struc-
tures without using some method of joining, such as rivets
or welds. And if such joints are used the fatigue strength
of the joints, rather than the fatigue strength of the ma-
terial in some ideal form, is evidently the upper limit,
or "100 percent" which good design may hope to achieve.

In latticed girders where the mutual support between
booms is concentrated in individual lattices which are usu-
ally shear carriers, a mere axial load on the girder will
cause some axial stress in the lattice as well, but the
lattice (unless it be pin-jointed, which it usually is not)
is also subjected to bending and shear and it in turn im-
parts secondary stresses to the booms. These may enhance
the effect of the presence of the rivets or welds.

In girders having booms with perforations, lightening
holes, indentations, Vierendeel webbing or other regularly
repeated variations of cross sections, there may be a com-
plex flow of stress around such holes or recesses accompa-
nied by stress concentrations at notch points. It has been
frequently observed that the weakest point of a structure
in fatigue is not always the weakest point in a static
test to destruction by a single load surge. In general,
severe stress concentration points are more likely to prove
points of weakness in fatigue than in static tests.

Naturally, if it were necessary to determine the fa-
tigue behavior of composite girders under all possible
loading conditions, tests would have to be made with ten-

sion, compression, bending and shear (if not torsion), and
critical combinations of these. To cover this huge field
of variations would be an extremely voluminous job. How-
ever, it is contended by some that even a few systematic-
ally selected tests may teach lessons of fundamental sig-
nificance for rational design. It is from this standpoint
that the present investigation was mostly focused on ten-
sion-compression tests.

There are many other influences besides the design
that bear an influence on fatigue strength. Among these
the following deserve attention:

Surface condition in regard to scratches and flaws,
especially at the rims or flanges of punched holes; also
corrosion by chemical or atmospheric agents. Many labora-
tory tests have shown that highly polished specimens have
fatigue strengths higher than similar specimens with im-
perfect surfaces, and that this difference in fatigue
strength is very marked. It is manifestly impossible to
obtain material on a production basis that is absolutely
free of all surface imperfections, and it is equally ap-
parent that some additional flaws cannot be avoided in the
handling of the material necessary during fabrication.
While careful handling will, of course, keep such flaws to
a minimum, this cause alone would produce a substantial
lowering of the fatigue strength of the girder as compared
with that of the carefully selected sheet specimen.

Some investigators have endeavored to determine the
influence of speed or frequency upon the number of cycles
sustained. With plastic materials undoubtedly higher fre-
quency permits less flow per cycle and therefore longer
resistance. Naturally, if a test speed were so high that
heating due to hysteresis would locally raise the tempera-
ture enough to affect the physical properties of the re-
gion surrounding the crack, such a test would be mislead-
ing.

It has been suggested that the repeated application
of load cycles at stresses below the ultimate fatigue
strength (of the critical stress concentration regions)
may improve the endurance of the system against subsequent
cycles exceeding the ultimate fatigue strength. If this
is a fact, then this phenomenon will undoubtedly work to
the benefit of airship structures in service where most
of the service load cycles are probably confined to moder-
ate stress amplitudes. The same, however, would apply in

some measure to our resonance machine tests where some ad-
justments often had to be made at moderate stress until
obnoxious secondary resonances or beats were eliminated
and the routine at the desired stress amplitude could be
begun.

NEW AXIAL FATIGUE TESTS ON AIRSHIP GIRDERS

<u>Description of fatigue machine</u>.[*]- Preliminary fatigue
tests of airship girders had led to the conclusion that
a great deal of valuable information might be gained by
making axial tension-compression fatigue tests on girders
in a stress range where the endurance would be of the or-
der of 10^4 to 10^7. In order to complete such tests in a
reasonable time per specimen, a resonance fatigue machine
developed and operated by the Goodyear-Zeppelin Corpora-
tion and suitable for frequencies between 30 and 100 cy-
cles per second had proven quite practical.

All girder specimens tested for the present report
were tested on this resonance fatigue machine, which is
shown in figure 2. In this machine the girder specimen
is subjected to alternating tension and compression cy-
cles. The girder is fitted with terminal shoes to which
are fastened heavy masses so chosen that the natural vi-
bration frequency of one mass against the other is of the
desired order of magnitude. The whole system is suspended
horizontally from soft springs whose spring constant is so
small that the natural frequency of the whole weight sus-
pended is much slower than the frequency of one weight
against the other. Thus practically no energy is dissi-
pated through the suspension into the building.

In order to set up stress vibrations in the girder
and maintain them at a given amplitude, an alternating
attraction and repulsion force is produced between the
masses. This force is controlled to alternate exactly
at the natural frequency of the girder-and-mass system.
The force required to sustain an elastic stress amplitude
is but a small fraction of the dynamic force exerted be-
tween the oscillating masses and the girder, which is the
force actually stressing the girder.

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[*]
 Subsequent to the presentation of this report a descrip-
tion of the Resonance Fatigue Machine was published in
the September 1937 issue of the Aero Digest.

The machine is built for resonance control of frequency. The push-pull oscillation is obtained by means of a reciprocating solenoid motor, the motor consisting of a steel encased direct-current magnet in whose steel circuit there is an annular air gap. A solenoidal armature is suspended by means of guides to oscillate axially through the radial magnetic field when energized by the alternating current of controlled frequency. The magnet is part of the mass at one end of the girder and the armature is fastened to the mass at the other end.

The control of the frequency of the armature current is obtained from a magnetic pick-up consisting of a similar but smaller system of magnet and armature in which a slight electric alternating current is induced by oscillation of the masses. The pick-up circuit is provided with a phase control by means of which adjustment for stable resonance is obtained. The alternating current for the machine is produced by two mercury-vapor grid-glow tubes in an inverter circuit.

The stroke or amplitude of the machine is measured by means of a small wedge-shaped target mounted on the drive rod. The target image as viewed through a microscope mounted on the other mass appears blurred during oscillation but its excursion amplitudes can be sharply made out. The stroke is read by gaging the location of the apparent intersections of the penumbra contours against the transverse scale. The amplitude is controlled by means of regulating the direct current input of the inverter circuit. This is accomplished by regulating either the input rheostat, or the direct-current voltage, or both, so that the stroke attains the desired value as seen in the microscope.

To keep accurate track of the number of cycles completed, a counter and a motor-driven log are provided.

Mounting of test specimens.- The girder ends of all the test specimens were cut square and solidly fastened into double-wall steel shoes by means of Libowitz metal to a depth of approximately 4-5/8 inches. A length of 49 inches between faces of the end shoes was adopted as the standard length for these tests, giving a distance of 37-3/4 inches between cast surfaces of the end shoes.

The stress variation was computed from the measured amplitude and the effective length of the specimen, the modulus of elasticity being assumed to be 10,300,000 pounds

per square inch. The effective length differed slightly
from the above length due to the method of end fastening,
the difference being estimated from static tests of long
and of very short specimens. (See fig. 3, showing a long
specimen.)

Description of tests.- The results obtained in this
present series of tests are given in table I, and are pre-
sented graphically on the SN curve shown in figure 4. The
tests may be divided into the following general groups ac-
cording to the types of girders tested:

1. GZ 3000907 - Specimens 1, 2, 7, 9, 11, 13, 16, 17*

2. GZ SX382   - Specimens 3, 5, 15**

3. LZ-126   - Specimens 8, 10, 18

4. "Shenandoah" - Specimens 12, 14

5. Bureau of Standards (riveted) - Specimen 4

6. Bureau of Standards (spot-welded) - Specimen 6

        *GZ 3000907 type girder was one of several types
            used on the "Macon".
      **GZ SX382 is an experimental type girder, devel-
            oped from a box-type girder by addition of
            closing channels in all four corners.

A more detailed grouping of the various specimens is
possible in order to illustrate the effect of certain vari-
ables upon the fatigue limits of such structures:

In determining the effect of increasing the material
thickness of the girder, specimens 7 and 9, of 0.040 gage
may be compared with specimens 11 and 13, of 0.023 gage.

The effect of omitting the 1/4-inch diameter hole of
the 3000191 perforation is indicated by a comparison of
specimens 1 and 2, without holes, and 11 and 13 with holes.
These four specimens are all of the same gage, namely 0.023.

The effect of omitting the perforations in the corner
closing channels is shown by a comparison of specimens 3
and 15.

Some indication of the comparative strength of spot-
welded and riveted connections is furnished by specimens 4
and 6.

The possible effect of splicing a girder is indicated by the two specimens 5 and 15, the former having a splice in one boom while the latter did not. It should be noted, however, that the splice in question was known to be in poor condition as the result of a previous static test, so that the comparison is hardly fair.

The number of cycles to both the first observed crack and to final failure of the specimens is given on the S-N graph of figure 4. At the rather high frequency at which these tests were run, it was, of course, impossible to determine the exact number of cycles at which each crack developed, but the test specimens were observed very closely throughout each test and the cracks were detected in most cases in their incipient stages.

In many of the tests, failures occurred with a distinctly audible cracking noise. In almost every case this sound was associated with a crack finally breaking through the edge of the material, completing the failure of a channel or boom.

Following are some pertinent observations made on each test. All tests were conducted in the Goodyear-Zeppelin Research Laboratory between October 1 and December 15, 1936:

Specimen No. 1: Specimen No. 1 was a special GZ 3000907-1 type girder, varying from the standard 3000907-1 girder only in that the small 1/4-inch diameter holes at the edges of the perforations were eliminated in both webbing and channel. (See fig. 3.)

The first crack occurred at the equator of a large perforation in the webbing, quickly followed by three additional cracks, all at equators of large perforations in the webbing and all near the end shoes. (See fig. 5.) Final failure of the girder took place through the large perforation opposite one of the original cracks. The failure did not pass through a rivet hole.

Specimen No. 2: Specimen No. 2 was identical to Specimen No. 1. No preliminary cracks were observed, failure of the webbing occurring with a snap through the webbing at the first large perforation. The failure did not pass through a rivet hole. The channels of the girder showed no outward signs of cracks at this point, the test not being continued to complete failure of the girder.

Specimen No. 3: Girder specimen No. 3 was a GZ SX382-2
type, with tubular corner booms. This type girder is es-
sentially a refinement of the GZ 3000901 type, the addi-
tion of perforated closing channels in all four corners be-
ing the major alteration. (See fig. 6.) This girder had
previously been given a static compression test in a length
of 55 inches, failing by buckling at a stress of 44,700
pounds per square inch. The damaged section had been cut
away and the remainder of the girder was used for this
fatigue test.

The first crack originated in a perforation of the
closing channel and was followed quickly by numerous oth-
ers. After 79,000 additional cycles the machine was
stopped and the girder closely examined. The four closing
strips were found to have a total of 37 cracks, all of
which originated at the perforations. No traces of cracks
could be found in the corner channels or webbings.

Final failure was in the form of a crack almost com-
pletely around the corner channel and the closing strip.
The crack was approximately 10 inches from the end shoe,
opposite a heart-shaped hole, and passed through a clos-
ing strip perforation and a rivet hole. Only one webbing
was cracked, this crack passing through a heart-shaped
hole at the cracked corner.

Of the 40 cracks found in the closing strips after
completion of the test, 26 were found opposite heart-shaped
holes, the other 14 being scattered. Only nine of the 40
cracks passed through rivet holes, the remaining showing
no inclination to progress through rivet holes, 8 in fact,
passing very near rivet holes without deviating to pass
through them.

Specimen No. 4: Specimen No. 4 was an N.A.F. riveted
girder referred to as 6351-2. (See fig. 7.)

The first crack occurred at the bend of the flanged
perforation, being at the equator of the first large hole.
(See fig. 8.) Additional cracks developed in rapid order,
always at the bend of the flange. The cracks all pro-
gressed in both directions, to the perforation and to the
edge of the webbing. There was always a distinct report
as the crack finally parted the material. Finally one
corner boom opposite the equator of the first perforation
from the end shoe cracked, the crack starting in the cor-
ner of the boom and progressing in both directions to the
edges.

Specimen No. 5: Specimen No. 5 was a special GZ SX382-2 type girder, being the same as Specimen No. 3 except that the perforations were omitted from the closing channels. This specimen was cut from an 11-foot girder previously tested statically to destruction. One corner channel of the test specimen had a splice approximately 6 inches from the end shoe. The girder was originally constructed with perforated closing channels, having been disassembled and rebuilt with blank closing channels for this test.

The first sign of failure was a crack which developed at the first rivet hole of the splice. This crack continued to develop until the corner channel and closing channel were completely severed.

The splice of the girder was of rather poor workmanship, not being a particularly tight job. Shortly after the test started, the splice angle was found to be noticeably warmer than the adjacent girder, and emitted a distinct vibrating noise, indicating the possibility of a loose rivet or rivets.

An attempt was made to continue the test of the girder to determine the number of cycles before failure of the remainder of the girder. Cracking of the webbing on both sides of the damaged channel soon followed, but no further damage developed and the three remaining corners showed no signs of failure after 1,170,000 cycles at approximately the same stress, namely, ±7,900 pounds per square inch.

Specimen No. 6: Girder specimen No. 6 was an N.A.F. girder, referred to as 6351-1B, being similar to Specimen No. 4 except that it was of spot-welded construction instead of riveted. In order to afford a direct comparison with the riveted girder No. 4, this girder was tested at the same stress. Due to warping of the girder in its construction, the girder could not be lined up as well in the stress machine as the remainder of the girders in the test program, but the very slight misalignment of the girder was not thought to be sufficient to materially affect the results.

The first crack was followed in rapid succession by numerous others. It was not possible to determine definitely whether the first crack occurred in the center of the girder or at one end, but all of the numerous cracks originated in the spot welds and progressed in both directions through both channels and webbing. (See fig. 9.)

No cracks originated at the flanges of the perforations as
was the case with Girder No. 4.

Specimen No. 7: Girder No. 7 was a standard
GZ 3000907-6 type girder with 1/4-inch diameter perfora-
tions. The first crack was near the center of the girder
and originated at a 1/4-inch diameter hole in the webbing.
A second crack occurred almost immediately, also in a 1/4-
inch perforation, but at one end of the girder. Approxi-
mately 3,500 cycles after the first crack, a third crack
was noticed in the opposite end of the girder from the
second crack, also through a 1/4-inch hole, but in the
channel. A fourth crack then originated in the webbing at
the large hole about 3/4-inch offset from the third crack.
This last crack then progressed through a rivet hole while
the crack in the channel simply progressed directly at the
edge of the channel, the corner being cracked completely.
(See fig. 10.)

Specimen No. 8: Specimen No. 8 was a "Los Angeles"
type longitudinal girder furnished by the Bureau of Stand-
ards. (See fig. 11.)

Failure occurred approximately 10 inches from the end
shoe, one corner cracking just outside the truss connec-
tion, the crack originating in that portion of the chan-
nel flange that is bent back for the truss.

The test of this girder as a whole was considered as
being very unsatisfactory. The girder vibrated consid-
erably transversely in the machine, weights having to be
attached to the central section of the girder to offset
this tendency. This transverse vibration was of suffi-
cient intensity to cause the result of the test insofar
as the number of vibrations to failure of the girder was
concerned to be doubted, but the test did indicate the
possible point of weakness of this type of girder in fa-
tigue.

Specimen No. 9: Specimen No. 9 was a standard GZ
type 3000907-6 girder, being identical to Specimen No. 7.

The first crack occurred at a 1/4-inch hole in the
webbing approximately 6 inches from the end shoes. 2,700
cycles later a second crack was observed at the opposite
end of the girder, also at a 1/4-inch hole in the web-
bing and approximately 6 inches from the end shoe.

In the final failure of the girder, the second crack
which had originated at a 1/4-inch hole in the webbing
progressed to the edge of the webbing, while a crack in
the channel developed at a point 1/2-inch offset from the
crack in the web. The failure of the channel was at a
heart-shaped hole and passed through a rivet hole.

Specimen No. 10: Specimen No. 10 was a "Los Angeles"
type girder furnished from the Bureau of Standards, being
similar to Specimen No. 8, with the exception of a U-shaped
channel riveted along its apex. In order to reduce the
troublesome transverse vibrations which were believed to
have led to premature failure of Specimen No. 8, the end
weights of the resonance machine for this test were in-
creased sufficiently to materially reduce the frequency of
vibration, resulting in the test being run very smoothly
with very little transverse vibration of the girder.

The first crack occurred in the U channel riveted
to the apex, approximately 12 inches from the end shoe.
A second crack, also in the U channel, originated 4,500
cycles later, 6 inches from the opposite end shoe. 23,400
cycles after the first observed crack, one of the bases
opposite the apex suddenly cracked completely through at a
truss connection 8 inches from the end shoe. It was con-
sidered quite possible that the first crack of the girder
originated at this point but was undetected because of
being under the truss.

The failure did not occur at a point where the flange
of the channel is bent back for the truss connection as
was the case with Specimen No. 8. It did pass through a
rivet, however, which had been drilled out and replaced by
the GZ shop in mounting the girder. The replaced rivet
was not in the proper heat-treated condition and may have
been a contributing cause to the failure. In addition,
the flange of the channel at the point of failure had been
slightly damaged. Both of these effects, however, are
thought to have been of minor significance insofar as the
total life of the girder was concerned inasmuch as cracks
had developed at other points of the girder.

Specimen No. 11: Girder specimen No. 11 was a stand-
ard GZ girder type 3000907-1, similar to Specimen No. 7,
but of lighter gage.

The first crack occurred at a 1/4-inch diameter per-
foration of the webbing 2 inches from the end shoe. 4,500

cycles later a second crack occurred, followed shortly by numerous other cracks, all originating in the 1/4-inch holes. Final failure of the girder came 2 inches from the end shoe, passing through a 1/4-inch hole in the web and a heart-shaped hole in the channel, the break of the channel and the webbing being approximately 1/2-inch offset.

Specimen No. 12: Specimen No. 12 was a "Shenandoah" type girder furnished by the Bureau of Standards and referred to as 55B Special. The apex of the girder failed without any observed preliminary signs of failure. The failure occurred 8 inches from the end shoe, passing through a grommet hole. (Grommets of approximately 1/4-inch diameter were located in the apex channel at 1-5/8 inch spacing.) The crack was at the first truss connection from the end shoe, not passing through a rivet hole. (See fig. 12.) While the crack passed through that section of the flange which is bent back for the truss connection, it is not known whether it actually originated there or in the grommet hole. Considering the very audible cracking noise with which the break occurred, which noise is usually associated with a crack finally breaking completely through a channel or webbing, it seems most probable that the crack originated in the grommet hole and then traveled to the edge of the channel.

Specimen No. 13: Specimen No. 13 was a standard GZ 3000907-1 type girder, being similar in every respect to Specimen No. 11.

The first crack occurred at a 1/4-inch hole in the webbing 4 inches from the end shoe. 4,500 cycles were required for this crack to progress to the edge of the webbing with 3,500 additional cycles being required before failure of the channel at a point 1/2-inch offset from the failure of the web. The crack in the channel passed through a heart-shaped hole and a rivet hole. At completion of the test, only one crack other than that at the point of failure could be found, this one originating at the 1/4-inch hole in the webbing at the opposite end of the girder.

Specimen No. 14: Specimen No. 14 was a "Shenandoah" triangular lattice-type girder similar to Specimen No. 12 but of lighter gage. This girder had 1/4-inch grommets in the apex at 1-5/8 inch spacing as did the former "Shenandoah" girder.

Although the girder was observed very closely through-
out the test, no preliminary signs of a crack or failure
could be found before total failure of the apex channel
occurred. As was the case with Specimen No. 12, the fail-
ure occurred at a grommet holt, approximately 12 inches
from the end shoe, but in this case did not pass through
a truss connection. Due to the suddenness of the failure,
it is impossible to say definitely where the crack origi-
nated, but it is thought to have had its origin in the
grommet hole and thence progressed to the edge of the
channel.

Specimen No. 15: Specimen No. 15 was a GZ SX382 type
girder, being identical to Specimen No. 5 except for the
omission of the splice and a difference in length. Like
Specimen No. 5, this girder had no perforations in the
corner closing channels, the test being intended to serve
as a comparison with Specimens Nos. 3 and 5, the former
having perforations in the closing channels and the lat-
ter a splice angle.

The first crack occurred at a small 1/4-inch hole in
the webbing, followed quickly by numerous others. The
first crack in the closing channel came 32,000 cycles
later, originating in the flange with an additional 39,000
cycles being required before a crack appeared in one of
the corner channels. After still another 137,000 cycles
a second crack appeared in a channel flange, with final
failure of the channel coming 16,000 cycles later. This
final failure was approximately 5 inches from one end
shoe. The crack in the corner channel passed through
rivet holes, but the crack in the closing channel did not.
One of the side webbings failed at the diameter of the
large perforation, while the other webbing failed through
a small 1/4-inch hole.

Specimen No. 16: Specimen No. 16 was a special type
girder closely resembling the standard GZ 3000907 type.
It was a rectangular box-type girder differing from the
907 girder only in the substitution of the 1000829 channel
for the 1000805 used in the 907 type. The 1000829 channel
has a 3/4-inch flange while the 1000805 has a 9/16-inch,
the channels otherwise being identical. Since this slight
difference is thought to be of no consequence insofar as
the fatigue strength of the girder is concerned, this
specimen is considered as a standard 907 type girder in-
sofar as this report is concerned.

The first crack occurred at a 1/4-inch hole in the
webbing and was followed quickly by numerous other similar
cracks at 1/4-inch holes, all in the webbings. After
108,000 additional cycles the first crack in the webbing
had progressed completely through to the edge of the web.
Four such cracks shortly progressed completely through the
webbing, but no signs of failure were observed in the
channels until final failure occurred with a break through
the channel corner 14 inches from the end shoe, passing
through 1/4-inch diameter holes of the webbings and through
a rivet.

The 1/4-inch diameter holes of this girder were very
deeply flanged for 0.045-inch material, with the proba-
bility that fabrication cracks around the holes were prob-
ably present before the fatigue test started. The early
appearance of cracks in the course of the test is thought
to have been caused by the further opening up and progress-
ing of these fabrication cracks, borne out by the fact
that final failure of the girder did not take place until
a very substantial number of cycles later.

Specimen No. 17: Specimen No. 17 was a special GZ
3000907 type girder similar to Specimen No. 16. As it was
believed that the early cracks which appeared at the flanges
of the 1/4-inch holes of Specimen No. 16 were the result of
fabrication cracks opening up after a comparatively few cy-
cles of stress applications, the 1/4-inch holes of the
webbing of Specimen No. 17 were drilled out slightly. The
flanges of the holes were not entirely removed in this
process, it merely being intended to remove sufficient of
the material to eliminate any fabrication cracks that
might have been present.

The first observed crack occurred at a 1/4-inch hole
of the webbing approximately 13 inches from the end shoe.
A second crack also at a 1/4-inch hole in the webbing,
came after 32,000 additional cycles, followed by a third
similar crack 25,000 cycles later. Final failure of one
corner of the girder occurred 11 inches from the end shoe
through a rivet hole where by an oversight the rivet had
not been squeezed. The failure to squeeze the rivet was
thought to have been a determining factor in the life of
the girder inasmuch as the failure passed through the
large perforations of both webbings instead of the small
1/4-inch diameter hole as usual. This is also borne out
by the fact that the failure did not occur at any of the
earlier cracked points of the webbings. Drilling out the

flanges of the 1/4-inch diameter holes of the webbing apparently had no noticeable effect on the fatigue life of the girder.

Specimen No. 18: Specimen No. 18 was a "Los Angeles" triangular lattice-type girder similar to Specimen No. 10. One slight alteration in the girder was necessary. The 0.039-inch U-shaped channel riveted to the apex did not extend entirely to the end of the girder, necessitating its removal and replacement by a similar 0.040-inch channel. This operation is thought to have had no effect on the test.

The first crack occurred 7 inches from the end shoe and originated in one of the base channels where the flange is bent back for the truss connection. Once the crack appeared, its progress was rapid, requiring only 3,600 additional cycles to progress completely through the base channel.

This specimen ran fairly smoothly in the resonance fatigue machine — that is, with little transverse vibration. No additional cracks could be found in the specimen after completion of the test.

DIGEST OF TEST RESULTS AND SURVEY OF RELATED LITERATURE

A survey of pertinent published and unpublished investigations dealing with the subject of fatigue strength of composite structures was made with special attention to those that have reference to aircraft structures or to the problems enumerated in the first section. Reports of cases of fractures due to accidental resonance of structures were not particularly emphasized in this study because they fail to give definite qualitative information though they are interesting inasmuch as they may reveal weak points in fatigue.

The necessity of limiting this discussion primarily to generalities and principles and of refraining from numerical comparisons is apparent when the type of structure tested is considered, for only one series of fatigue tests has been found on structures which closely resembled the girder types tested at the Goodyear-Zeppelin Corporation. These tests were conducted abroad and while the results are not available for publication, they are in excellent

agreement with the results obtained in our own laboratory.
These tests abroad were conducted under alternating axial
compression and tension stresses, with tension peaks ranging
from 17,000 pounds per square inch to 23,000 pounds per
square inch stress at a frequency of 30 cycles per minute.
Failures in this series of tests occurred in similar re-
gions as did the group of girders tested by the Goodyear-
Zeppelin Corporation with approximately the same spread
insofar as consistency of results is concerned.

That the physical characteristics of the material are
fundamental factors governing the endurance properties of
a structural element is agreed upon by all investigators.
However, numerous tests have indicated that there is no
definite relationship between endurance limit and other
mechanical properties (references 1 and 3) and in particu-
lar that tensile strength alone is not necessarily any
criterion of fatigue strength.

In figure 1 are reproduced curves of the endurance
properties of the aluminum alloys 17ST and 17SRT. It is
readily seen from the figure that 17SRT does not show an
increased fatigue strength over that of 17ST commensurate
with its increased static strength. Similar results are
shown by fatigue tests conducted on seamless aluminum and
aluminum-alloy tubing (reference 2), in which tubes of
widely different tensile strengths (17ST and 51SW) have
been found to have practically the same endurance limit.

It is of interest to note the range of endurance ra-
tios (endurance limit to tensile strength) of the aluminum
alloys as found by the Aluminum Company of America in tests
conducted in their laboratories (reference 4). The higher
values of the ratio were found for the alloys of low alloy
content in the annealed, wrought condition. According to
Templin (reference 4), the endurance ratios of these low
alloy content alloys, in the properly annealed, wrought
condition would, under suitable testing conditions, be
found in the neighborhood of 0.5. With the higher alloy
content alloys, the tests revealed greater variations in
the endurance ratios. Heat treatment and cold working
improve both the fatigue properties and tensile strength
of the various alloys, causing changes in the endurance
ratios such that the ratio varies considerably for the
different alloys from approximately 0.19 to 0.55. Inas-
much as the beneficial effect of heat treatment and cold
work is usually greater on the tensile strength than on
the fatigue properties of the alloys, a decrease of the
endurance ratio usually accompanies either heat treatment
or cold working.

Although girders of different aluminum alloys were tested in the GZ fatigue tests, it is not possible to definitely establish that variations in the results were due to differences of material. The "Shenandoah" type girders were fabricated of 17ST, the Goodyear-Zeppelin Corporation girders were of 17SRT, while the material for the "Los Angeles" girders was more similar to 17ST than to 17SRT. Differences in girder types and possible corrosion are thought to have been as important factors in the results obtained with the "Los Angeles" and "Shenandoah" girders as the effect of material differences.

The Aluminum Company of America fatigue curves referred to above as figure 1 of this report, indicate an improvement due to cold rolling in the fatigue strength of the SRT alloys at high stresses, but this improvement fades away as the longer endurances of low stress amplitude are approached. This phenomenon of increased fatigue strength due to cold working has been found by other investigators (reference 5).

O. J. Horger (reference 6), in an interesting series of tests on steel specimens, concluded that fatigue strength could be increased by as much as 32 percent in some cases by cold rolling. According to Horger, his results indicated that strain hardening (reference 7) in the absence of residual stresses was directly responsible for the large increase in fatigue strength. That the beneficial effect of cold working is not so marked for aluminum alloys and other nonferrous metals is generally agreed and is borne out by the Aluminum Company tests. The present series of GZ tests cannot be considered as giving any indication of the beneficial effects of cold rolling of the material inasmuch as all girders tested with the exception of the "Shenandoah" girders were of cold-rolled material and no comparative results were obtained.

Numerous attempts have been made by various investigators to determine the effect of "coaxing" the material, a process defined by Gillet (reference 8) and Mack as that of gradually increasing the stress during the endurance test. Most of these tests have shown that the effect is beneficial, but the results have been widely scattered insofar as the degree of this beneficial influence is concerned or the extent to which it can be carried before the effect becomes harmful rather than helpful. A series of tests conducted by R. R. Moore (reference 9) indicated that understressing had a favorable influence on the en-

durance properties of naval brass, magnesium, and a magne-
sium-aluminum alloy, but showed no decided improvement
for aluminum, leading him to believe that in the case of
aluminum, if any beneficial results are to be obtained,
the understressing must be done at lower stresses than
those with which he experimented, namely, 10,000 pounds
per square inch. Moore finally concluded from these tests
that the possibilities of improvement by understressing
are not as great for the light nonferrous alloys as with
the heavy nonferrous and ferrous alloys and that his tests
had not demonstrated that the value of the endurance limit
could actually be raised for the light nonferrous alloys,
as was done on steels. H. F. Moore and T. M. Jasper (ref-
erence 10) have investigated the effect of understressing
on various metals and found that certain metals showed a
marked increase in fatigue strength while others showed
comparatively little.

The GZ tests would seem to confirm the belief that
understressing has little effect upon the fatigue proper-
ties of aluminum alloys. During the tests some of the
specimens were subjected to a number of cycles of stress
reversals at stresses below the desired and final stress
at which the test was run, but the effect of this under-
stressing, which in most cases consisted of comparatively
few cycles, was not apparent in the results.

A factor of importance in the endurance of any struc-
tural element is the range of stress to which the element
is subjected.

Well known is the fact, expressed by K. Schaechterle
(reference 11), that the strength under many repetitions
of loading of composite structures depends upon the range
of stress — that, for example, if there is no reversal of
stress in a cycle and the minimum stress is zero, the
strength under this condition is greater than if the
stresses are completely reversed each cycle at the same
peak stress.

In the GZ tests conducted on the resonance fatigue
machine, the stresses imposed upon the test specimen were
completely reversed, but in earlier tests conducted on
an Amsler Universal testing machine, stresses were not re-
versed, the range being from practically zero to the de-
sired tension peak. Since no tests were run on the Amsler
machine at reversed stress cycles, no very accurate com-
parisons can be drawn, but if the Amsler tests are com-

pared with the resonance machine tests, the results are seen to fall in nearly the same region for both types of stresses, reversed and pulsating. The same is true if the results of foreign tests previously mentioned, in which the stresses were reversed at a frequency of 30 cycles per minute, are compared with the GZ Amsler test results where the frequency was approximately the same and the stresses were not reversed. While it is admitted that accurate comparisons of such test results cannot be made unless all test conditions are duplicated as nearly as possible, these results would at least seem to indicate that for girder types of the nature and materials tested the range of stress is not as important as the results of most investigations would indicate, and that the maximum tension stress is perhaps the most important criterion. It is, of course, possible that differences in methods of stress determination in the different types of tests and the widely different frequencies at which they were run might overshadow any possible variation due to differences of stress range.

The effect of the frequency of stress cycles on the endurance properties of materials is a moot question. Most investigators are inclined to the belief that for "ordinary" speeds of stress reversals, the endurance limit is independent of the frequency of vibration (references 11, 12, and 13). In contrast to this, however, tests have been conducted by Graf (reference 14) on certain supposedly identical riveted connections for the purpose of determining the influence of load frequency on fatigue strength which have indicated that the number of load repetitions which the specimens could stand before failure was larger for 350 load changes per minute than for 10 per minute. These tests were not conclusive, however, inasmuch as comparatively few specimens were tested, the results were not consistent, and the difference in cycles withstood before failure was logarithmically small.

Actually, no very convincing evidence has been found of the effect of frequency of load applications at low cycles on endurance properties of materials. C. F. Jenkins, in a series of tests in 1924 (reference 15) found a slight increase of fatigue strength at high frequencies - frequencies of his tests varying from 50 cycles per second to 2,000, the largest increase of fatigue strength found being 15 percent at the latter frequency. In later tests (reference 16), Jenkins and Lehman continued this investigation at still higher frequencies, up to 20,000 cycles

per second, and recorded increases of fatigue limits as
high as 60 percent with certain steels and 34 percent for
a rolled aluminum alloy. Jenkins' tests showed, however,
that for frequencies under 500 cycles per second, changes
of frequency have practically no effect on the fatigue
limit.

The GZ resonance machine tests were conducted at fre-
quencies of from 51 to 93 cycles per second, which is ad-
mittedly higher than frequencies which the girders might
be expected to encounter in actual service, but in the
light of commonly accepted thought on this subject by most
investigators, it is felt that this frequency has not ob-
scured the results. At any rate, corresponding tests made
on the slow reversal axial stress machine at frequencies
of only 3/4 cycle per second are in sufficiently close
agreement to justify that belief.

Ewing (reference 12) has shown, and others are in ac-
cord with him, that the endurance limit is usually higher
if periods of rest occur between the loadings, a factor
which will favor the girder in actual service as compared
with the conditions of the test.

Numerous corrosion fatigue tests have been made on
aluminum and other nonferrous metals as well as on the
ferrous metals (references 17, 18, 19, and 20). It has
been shown, and should be emphasized, that the static ten-
sile strength may be unaffected by the corrosion, whereas
the resistance to repeated stresses is considerably af-
fected (reference 21). Reductions of as much as 35 per-
cent in the endurance limit of aluminum alloys due to cor-
rosion have been obtained with no reduction in tensile
strength of the material.

D. J. McAdam (reference 22) in investigating the ef-
fect of corrosion, also studied the corrosion-fatigue ef-
fect - that is, the influence of simultaneous corrosion
and fatigue. He has shown that corrosion simultaneous
with fatigue has a much more severe effect on the endur-
ance limit than does more severe corrosion prior to fa-
tigue. These tests reveal the corrosion-fatigue suscepti-
bility of aluminum alloys and emphasize the usefulness of
protective coatings. The corrosion-fatigue limits for the
tempered and annealed duralumin have been shown to be prac-
tically the same, in this respect being similar to steel.

Of the girder specimens tested in our own laboratory,

only the two "Shenandoah" girders appeared to have had
their endurance properties affected to any extent by cor-
rosion. These two girders, fabricated about 1922, had no
protective coating and were ostensibly corroded. Their
low fatigue limits as compared with the remaining speci-
mens can be reasonably explained to be the result of this
corrosion, although stress concentrations around the grom-
met holes might actually have been the determining fac-
tors. The "Los Angeles" girders, fabricated about 1924,
had a protective coating of varnish that is likely to have
retarded their corrosion materially. The inconsistency
of the results obtained with these "Los Angeles" girder
specimens, however, may in part be due to some corrosion,
although other factors affected the tests of this partic-
ular girder type as explained under Description of the
Tests.

Much thought has been given to the problem of stress
concentrations accompanying any irregularities in the sur-
face of a structure. In the airship girders tested such
stress concentrations result from perforations, flanges,
indentations, rivets, etc.

The notch sensitivity of metals in fatigue has been
investigated in various tests (references 23, 24, 25, and
26), but worthwhile results of a nature to be of benefit
to the designer are still few. Points of stress concen-
tration are of particular importance in structural parts
subjected to reversals of stress, fatigue cracks general-
ly starting at such points (references 27, 28, and 29).
Tests have indicated, however, that while there is a de-
cided reduction in the fatigue strength due to stress
concentrations, this reduction is usually found to be
smaller than would be expected from the magnitude of the
calculated stress concentration (reference 30). This dis-
crepancy is usually explained as being the result of plas-
tic flow, the actual stress at the place of high stress
concentration being much smaller than the calculated
stress, this being particularly true for the more ductile
materials (reference 31). Moore (reference 9), however,
has arrived at the opinion that the property of ductility
alone as measured by elongation, while it may contribute
somewhat to the enhancement of the endurance properties
of a notch specimen, is not necessarily the controlling
factor.

Stress concentrations at holes have been studied by
numerous investigators (references 32, 33, 34, and 35).

Their work throws much light on how the severity of stress
concentration at the edge of a hole depends upon the shape
of the hole, upon its orientation with regard to the di-
rection of stress, and upon the size of the hole as com-
pared to the width of the surrounding material. The effect
of semicircular grooves has been studied by Preuss (refer-
ence 36), while McAdam (reference 37) has tested specimens
with similar triangular grooves. All of these tests have
indicated that the weakening effect of stress concentra-
tions in endurance tests varies greatly with the material
and the actual shape and type of structural element being
tested.

     The Goodyear-Zeppelin tests have clearly pointed out
certain points of maximum stress concentration in the gird-
ers tested. It would seem that the comparatively low fa-
tigue strength of girders as compared with the fatigue
strength of the material of which they are fabricated, is
primarily due to stress concentrations and to residual
fabrication stresses. The consistency with which the 907
type girders failed at the small punched and flanged hole
and the two failures at the flanges of the large hole when
the small holes were omitted on two specimens, apparently
indicates the presence of high tensile hoop stresses at
these points. The presence of these residual hoop stresses
is borne out by the tendency of the flanged hole to crack
radially from the lip during fabrication. The small but
seemingly well established improvement in the fatigue prop-
erties of the 907 type girder found when the small 5/16-
inch diameter hole was reduced to 1/4-inch diameter, serves
to confirm the belief that the degree of stress concentra-
tion is affected by the size of the hole as compared with
the width of the material.

     The early failures of the SX 382 type girder with the
perforated closing strips also showed the effect of stress
concentrations at the holes. The many cracks which devel-
oped in this specimen were all at the holes of the closing
strip and perpendicular to the direction of stress. That
the holes were a source of stress concentrations was indi-
cated by the longer life of the same girder type without
perforations in the closing strips.

     While several girders failed at rivet holes, rivet
holes were not a predominant source of failure, indicating
that though they are points of stress concentration, riv-
ets are not necessarily the weakest point of girders in
fatigue.

The many cracks which developed in the flanges of the perforations on the N.A.F. girder of riveted construction indicated the presence of high residual stresses for this type of flange.

Surface finish has been shown to have a decided effect on fatigue tests (references 38 and 39). For example, (reference 40), Moore has shown the following results for various finishes on certain steel specimens, with 100 percent being taken as the endurance limit for highly polished specimens: ground finish 89, smooth turn finish 84, rough turn finish 81. Comparative fatigue tests on 17ST sheet, plain and anodized with sulphuric-acid electrolyte, have been made by the Aluminum Company of America, in which the anodizing appeared to have been beneficial. No comparative endurance tests on aluminum alloy specimens anodized with chromic-acid electrolyte are known to the authors.

Since the effect of surface finish is believed to depend somewhat upon the thickness of the material, the effect of material thickness on the fatigue properties of composite structures such as airship girders was studied in the Goodyear-Zeppelin tests. An increase in the gage apparently increased the fatigue limit. The gages used in the tests were 0.023 inch and 0.040 inch.

While in most cases girders of exactly the same kind which were tested gave relatively consistent results, the difference in results obtained with specimens 10 and 18 is a warning not to draw too definite conclusions from so limited a program.

Few tests of a comparative nature which might indicate the relative fatigue strengths of riveted and welded connections of aluminum alloy structures have been made. Stress concentrations are, of course, known to exist at both rivets and welds, these points being common points of fatigue failures. The fatigue behavior of spot-welded aluminum connections has long been questioned due to the known low endurance properties of the aluminum alloys in the annealed condition. The fact that the annealed condition of the material resulting around a spot weld is also a point of high stress concentration accentuates the unfavorable conditions insofar as fatigue strength is concerned (reference 41).

Fatigue tests carried out by D.V.L. (reference 42) on

spot-welded steel spars have indicated that it is in the
circle of annealed metal immediately surrounding the weld
that fatigue cracks originate rather than in the weld it-
self. Minute cracks in the weld itself, however, and es-
pecially at the edge of the weld, may lead to a low endur-
ance strength.

In the one spot-welded girder tested at the Goodyear-
Zeppelin Corporation, practically all of the many cracks
which developed, originated in the weld and not in the an-
nealed region immediately surrounding the weld.

CONCLUSIONS FROM TESTS

Numerous lessons can be learned concerning the fatigue
properties of composite structures in general and certain
airship girder types in particular as a result of the in-
vestigation conducted at the Goodyear-Zeppelin Corporation.
A brief summary of these lessons follows:

1. The endurance properties in reversed axial load
    tests of such girders as were tested, i.e.,
    GZ 3000907 box-type, GZ SX382 truss-type,
    "Los Angeles" truss-type, "Shenandoah" truss-
    type, and N.A.F. box-type, are considerably
    lower than the endurance properties of sheet
    specimens of the material of which the girders
    are fabricated as given by reversed bend tests.
    No definite factor has been established, but
    in general the stresses withstood by the gird-
    ers tested for a given number of reversals,
    were found to be approximately one-third of
    the corresponding stresses for the sheet mate-
    rial as determined by the Aluminum Company of
    America in bending tests. No comparative val-
    ues for the endurance of the sheet material
    when subjected to reversal axial load are avail-
    able. The results from tests of the GZ 3000907
    type girders held fairly closely to the above
    factor, while some of the remaining girders ex-
    hibited fatigue properties considerably lower,
    due to the influence of various factors previ-
    ously discussed.

2. Stress concentrations definitely affect the fa-
    tigue limit of girders. The small diameter

hole in the GZ 3000907 type girder is the weakest point of that particular girder type in fatigue. Decreasing the size of the small hole from 5/16-inch diameter to 1/4-inch diameter and at the same time increasing its distance from the edge of the material slightly gives an increase in the fatigue properties of the girder. However, omission of the 1/4-inch hole entirely indicated only a very slight further improvement in the fatigue strength of the girder.

3. The region surrounding rivets, though subject to stress concentration and occasional failure in fatigue, need not necessarily be the weakest point in fatigue of composite girders, failures in the girders tested showing no decided tendency to pass through rivet holes. However, girders which failed at rivets were in general no better than those which failed elsewhere, indicating that rivets affect the fatigue strength about as much as other sources of stress concentration in the girders tested.

4. Grommet holes are suspicious points. They and any unfilled holes are more apt to be points of origin of fatigue failures than rivet-filled holes.

5. Corrosion apparently weakens such structures in fatigue.

6. An increase in fatigue resistance seems to accompany an increase in the thickness of the material.

7. The single spot-welded girder tested indicates a weakness in fatigue for this method of joining.

8. The type of flange used at holes is an important factor in the fatigue properties of such structures, fatigue cracks generally originating at these points. The type of flange used on the special type of girder furnished by the Navy Department appeared inferior in fatigue as compared with the Goodyear-Zeppelin type of flange.

RECOMMENDATIONS FOR FUTURE LABORATORY TESTS

A continuation of the present laboratory investiga-
tion of the fatigue properties of airship girders is rec-
ommended with the following suggestions offered as a pos-
sible guide to such future investigations:

1. In future fatigue tests on any one type of gird-
    er, it would be desirable to investigate the
    effects of the many variable factors entering
    into its fatigue properties. Testing various
    girder types gives interesting results but in
    order to arrive at definite conclusions, it
    would help if a single girder type is selected
    as an example and many tests carried out on
    this one type with a view to determining the
    effect of variations in loading, stress range,
    material differences, gage variations, varia-
    tions of the perforation pattern and method
    of joining.

2. Little is known concerning the endurance strength
    of the light alloys under other than flexural
    stress reversals. It would seem desirable to
    run systematic fatigue tests on aluminum-alloy
    thin-walled specimens under symmetric and un-
    symmetric tension-compression cycles between
    various maximum and minimum stress limits.
    It is also highly desirable that such tests be
    conducted on actual girder specimens.

3. Tests to investigate the shear fatigue of girders
    would be of interest. To determine the fatigue
    behavior of such structures under all possible
    loading conditions is perhaps impractical, but
    systematically selected tests of combinations
    of tension, compression, bending, and shear
    should reveal lessons of fundamental impor-
    tance.

4. More systematic investigations could be made to
    determine residual stresses and the degree of
    stress concentrations existing around perfora-
    tions and at other irregularities of the gird-
    er surface, with a view to reducing the sever-
    ity of such concentrations wherever possible.

5. The effect of occasional cycles of overstress on the fatigue properties of girders should be investigated.

6. More thorough comparative tests of spot-welded and riveted girders should be made before any definite conclusions can be drawn concerning their comparative fatigue properties.

7. A systematic series of corrosion fatigue tests on girders would be of assistance in attempting to determine the useful life of such structures.

8. The fatigue properties of various types of girder splices should be investigated.

Goodyear-Zeppelin Corporation,
    Akron, Ohio, September 1937.

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TABLE I OF TEST SPECIMENS

| GIRDER TYPE	MATERIAL	GAGE CHANNEL IN.	WEBBING IN.	CLOSING STRIP IN.	NOMINAL AREA COMPR. SQ.IN.	TENSION SQ.IN.	WGT/FT #	FREE LENGTH IN	STROKE IN	STRESS RANGE #/□"	FREQUENCY CPS	CYCLES TO FIRST CRACK	ADDITIONAL CYCLES TO FAILURE
1.) GZ 3000907-1 SPECIAL 5⅛" x 5⁷⁄₁₆ NO SMALL HOLES	17 SRT	.023	.023	—	.212	.195	.378	37¾	.060	±13,300	58	80,000	10,800
2.) GZ 3000907-1 SPECIAL 5⅛" x 5⁷⁄₁₆" NO SMALL HOLES	17 SRT	.023	.023		.212	.195	.378	37¾	.078	±19,700	56	28,350	—
3.) GZ 5x382-2 6⁷⁄₁₆" x 6¹³⁄₁₆" PERFORATED CLOSING STRIPS	17 SRT	.0285	.034	.028	.677	.611	1.039	36½	.030	±7,900	93	313,000	289,000
4.) N.A.F. #6351-2 6⁹⁄₁₆" x 6⅞" RIVETED CONSTRUCTION	24 SRT ALCLAD	.0321	.0327		.686	.621	1.072	37¾	.030	±7,600	92	298,000	144,000
5.) GZ 5x382-2 SPECIAL 6⁷⁄₁₆" x 6¹³⁄₁₆" NO HOLES IN CLOSING STRIP SPLICE IN ONE CORNER	17 SRT	.0285	.034	.028	.747	.681	1.075	37¾	.031	±7,900	81	680,000	7,200
6.) N.A.F. #6351-1B 6⁹⁄₁₆" x 6⅞" SPOT WELDED CONSTRUCTION	24 SRT ALCLAD	.0322	.0322		.684	.689	1.011	37¾	.030	±7,600	77	64,200	19,000
7.) GZ 3000907-6 5⅛" x 5⁷⁄₁₆ SMALL HOLES ¼"	17 SRT ANODIZED AND PAINTED	.040	.040		.366	.335	.631	37¾	.059	±15,000	72	149,500	11,000
8.) LOS ANGELES 10" HIGH 8⅛" WIDE TRIANGULAR LATTICE TYPE LONGITUDINAL	AL. ALLOY GERMAN VARNISHED	CHANNELS APEX .078 BASE .064 LATTICES SIDES .024 BASE .020			.415	.372	.766	37¾	.039	±11,500	79	55,500	11,400
9.) GZ 3000907-6 BOX GIRDER 5⅛" x 5⁷⁄₁₆" SMALL HOLES ¼"	17 SRT ANODIZED* AND PAINTED	.040	.040		.366	.335	.631	37¾	.059	±15,000	72	134,000	38,000
10.) LOS ANGELES 10" HIGH 8⅛" WIDE TRIANGULAR LATTICE TYPE BOW LONGITUDINAL	AL. ALLOY GERMAN	CHANNELS APEX .038/.039 BASE .063 LATTICES SIDES .024 BASE .020			.400	.362	.748	37¾	.039	±10,000	62	500,000	23,400
11.) GZ 3000907-1 BOX GIRDER 5⅛" x 5⁷⁄₁₆" SMALL HOLES ¼"	19 SRT ANODIZED* AND PAINTED	.023	.023		.212	.195	.373	37¾	.059	±15,000	54	69,000	36,000
12.) SHENANDOAH GIRDER 14³⁄₃₂ HIGH 10³⁄₃₂ WIDE TRIANGULAR LATTICE TYPE	AL. ALLOY	CHANNELS APEX .053 BASE .046 LATTICES SIDES .020 BASE .016			.295	.260	.690	37¾	.039	±10,000	51	117,000	—
13.) GZ 3000907-1 BOX GIRDER 5⅛" x 5⁷⁄₁₆" SMALL HOLES ¼"	17 SRT ANODIZED* AND PAINTED	.023	.023		.212	.195	.373	37¾	.059	±15,000	53	66,500	8,000
14.) SHENANDOAH GIRDER 14³⁄₃₂ HIGH 10³⁄₃₂ WIDE TRIANGULAR LATTICE TYPE	AL. ALLOY	CHANNELS APEX .0385 BASE .038 LATTICES SIDES .020 BASE .016			.232	.203	.620	37¾	.039	±10,000	58	104,000	—
15.) GZ 5x382-2 SPECIAL 6¹³⁄₁₆" x 6¹³⁄₁₆" NO HOLES IN CLOSING STRIP	17 SRT	.0285	.034	.028	.747	.681	1.075	35	.035	±9,700	82	925,000	224,000
16.) GZ 3000907-8 SPECIAL 5⅛" x 5⁷⁄₁₆" SMALL HOLES ¼"	17 SRT ANODIZED* AND PAINTED	.045	.045		.440	.407	.742	37¾	.039	±10,000	75	330,000	720,000
17.) GZ 3000907-8 SPECIAL 5⅛" x 5⁷⁄₁₆" SMALL HOLES ¼"	17 SRT ANODIZED* AND PAINTED	.045	.045		.440	.407	.742	37¾	.039	±10,000	75	306,000	196,000
18.) LOS ANGELES 10" HIGH 8⅛" WIDE TRIANGULAR LATTICE TYPE BOW LONGITUDINAL	AL. ALLOY GERMAN	CHANNELS APEX .040/.039 BASE .063 LATTICES SIDES .024 BASE .020			.400	.362	.748	37¾	.039	±10,000	62	174,000	3,600

*CHROMIC ACID ELECTROLYTE.

Fig. 1
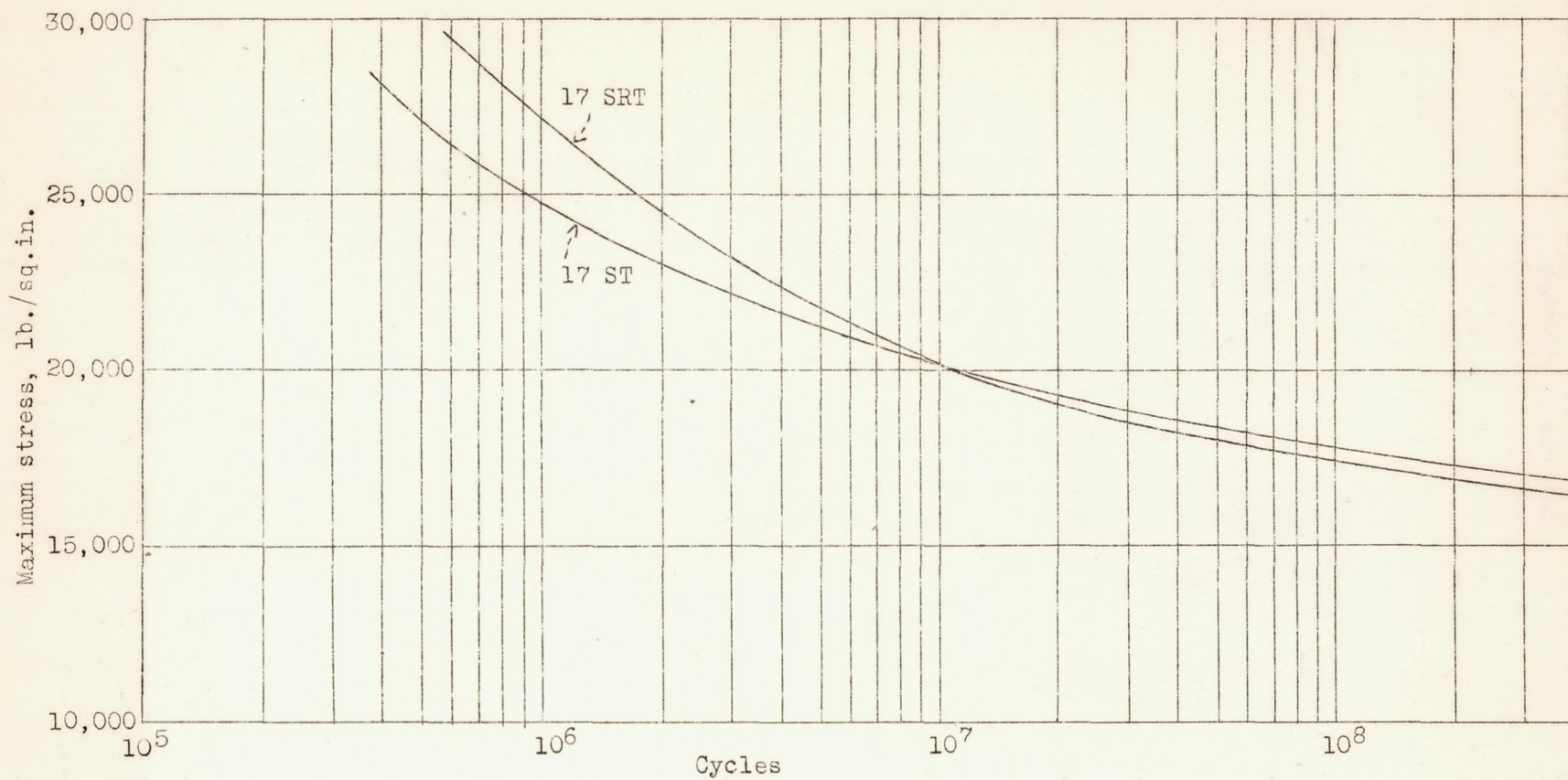
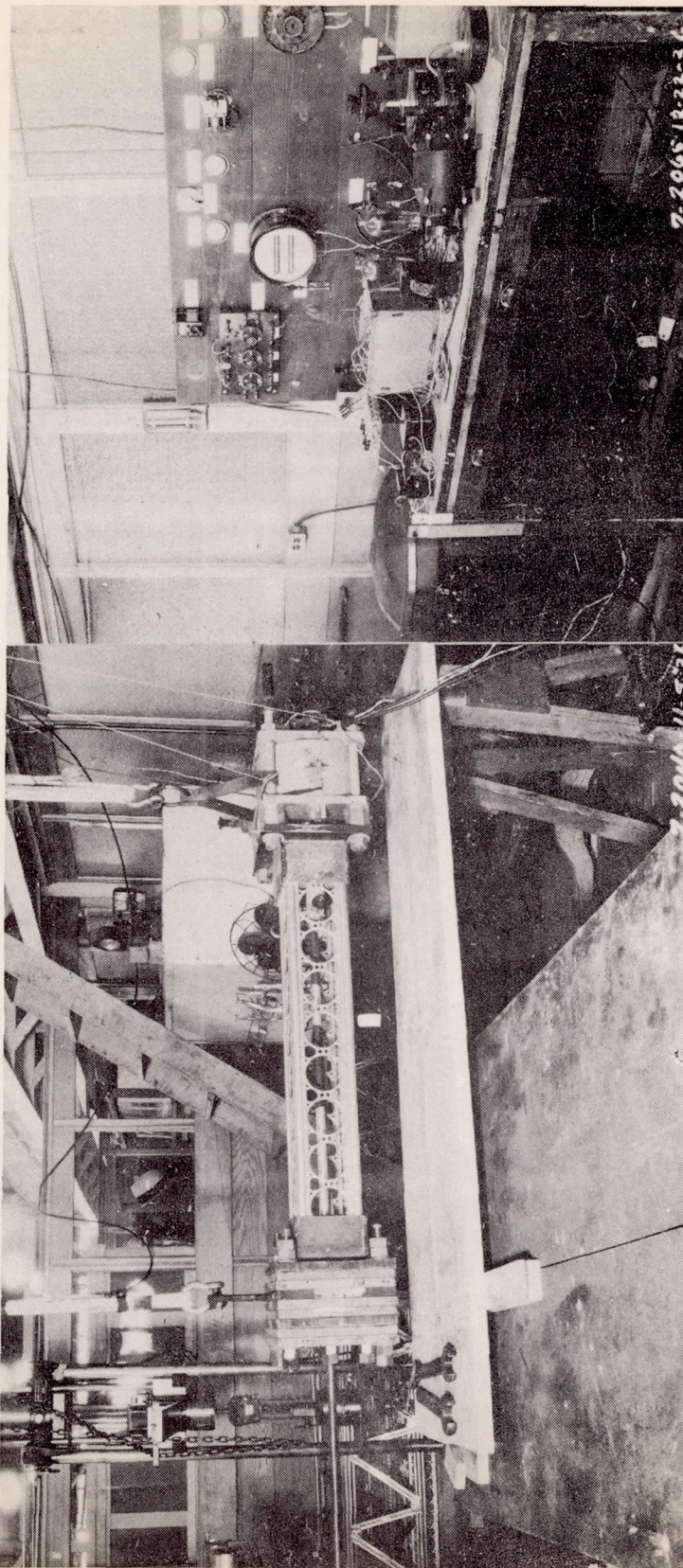Figure 1.- Reversed bending fatigue curves for 17 ST and 17 SRT sheet, (from Aluminum Co. of America).
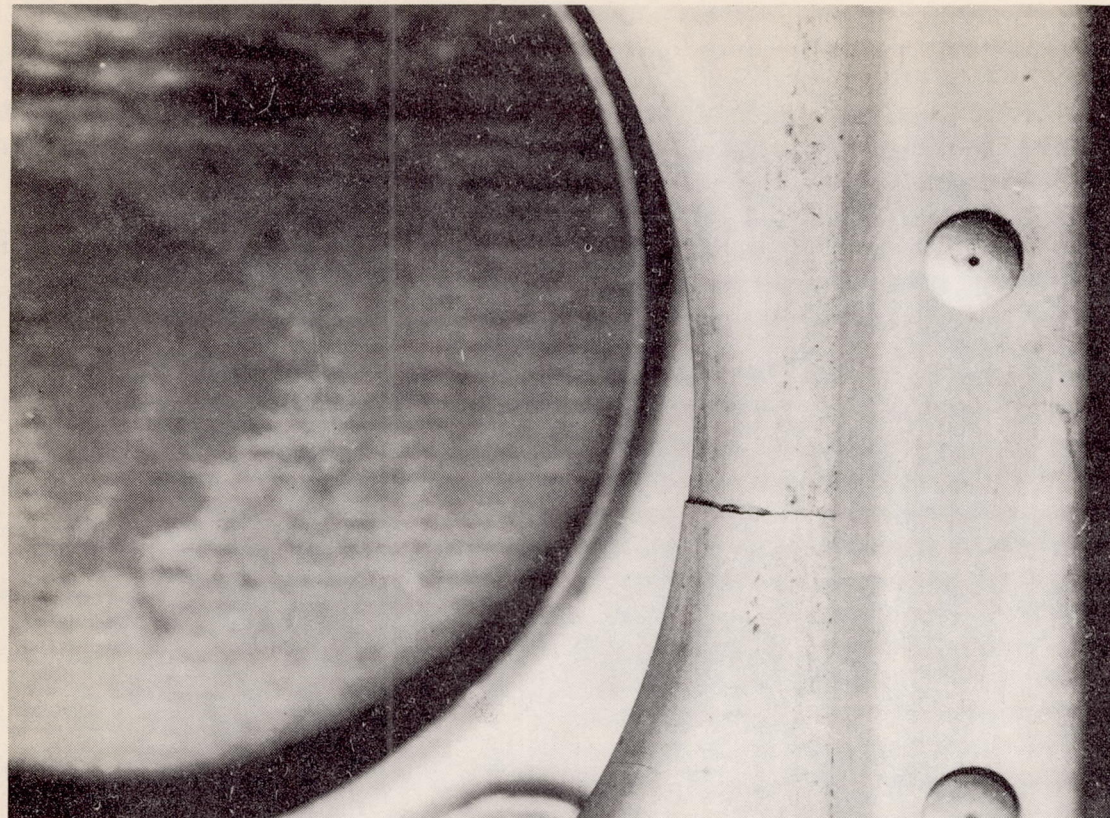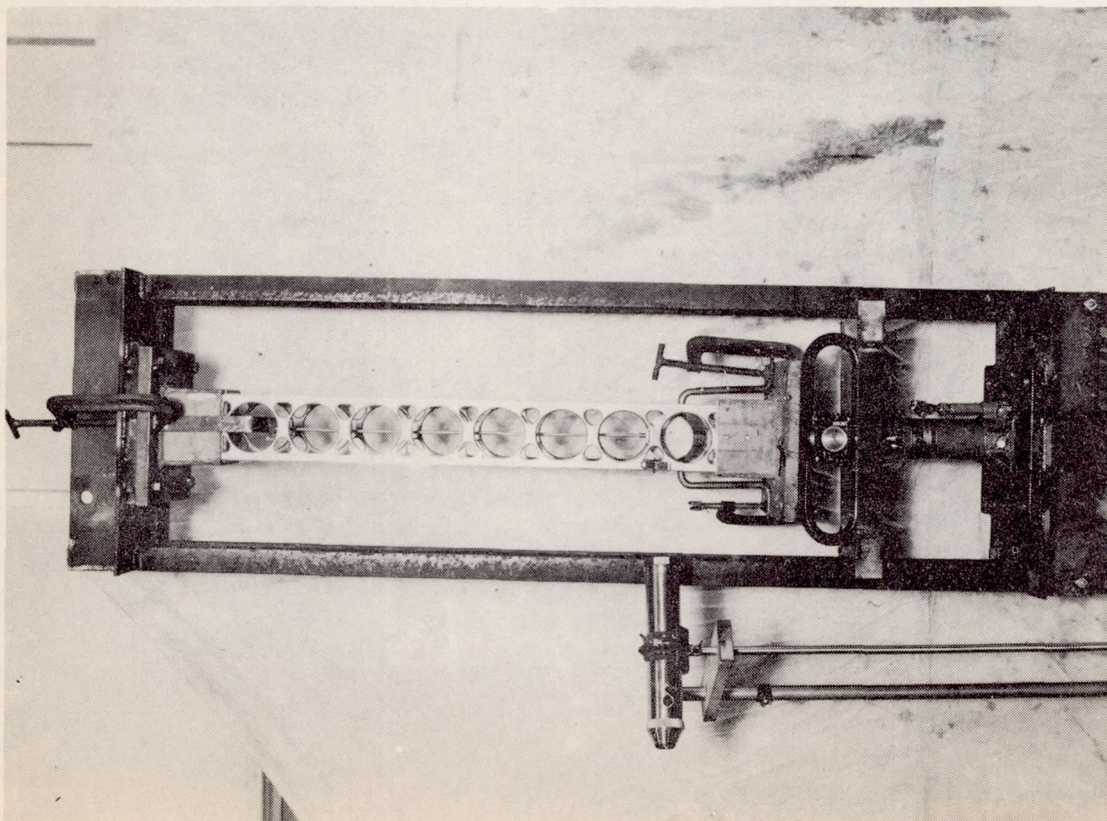
Fig. 2

Figure 2.

Figure 5.
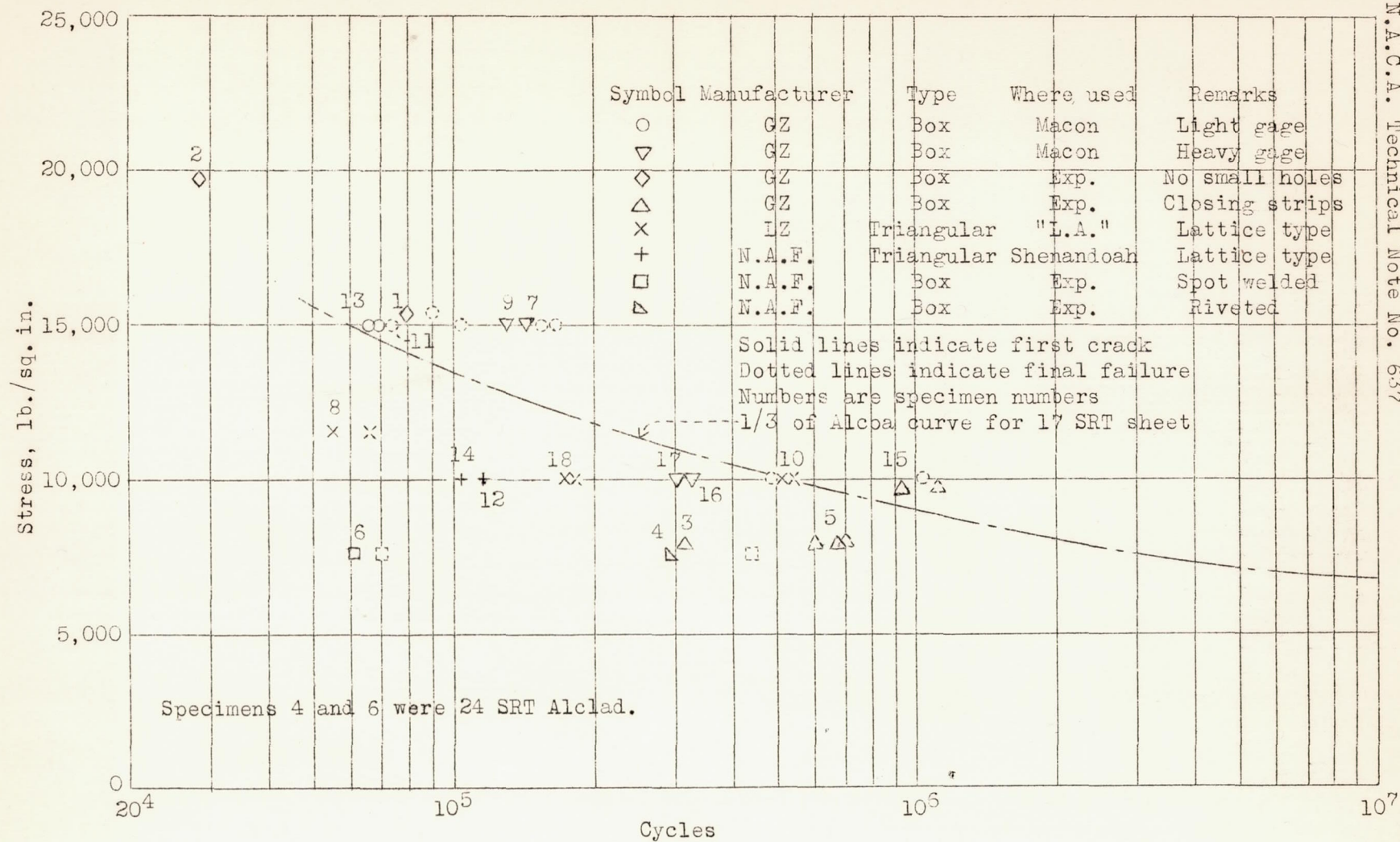
Figure 3.

Stress, lb./sq. in.

25,000

20,000

15,000

10,000

5,000

0

Symbol	Manufacturer	Type	Where used	Remarks
○	GZ	Box	Macon	Light gage
▽	GZ	Box	Macon	Heavy gage
◇	GZ	Box	Exp.	No small holes
△	GZ	Box	Exp.	Closing strips
×	LZ	Triangular	"L.A."	Lattice type
+	N.A.F.	Triangular	Shenandoah	Lattice type
□	N.A.F.	Box	Exp.	Spot welded
◁	N.A.F.	Box	Exp.	Riveted

Solid lines indicate first crack
Dotted lines indicate final failure
Numbers are specimen numbers
1/3 of Alcoa curve for 17 SRT sheet

Specimens 4 and 6 were 24 SRT Alclad.

10^4 10^5 10^6 10^7

Cycles

Figure 4.

Fig. 4

Figure 6.

Figure 7.

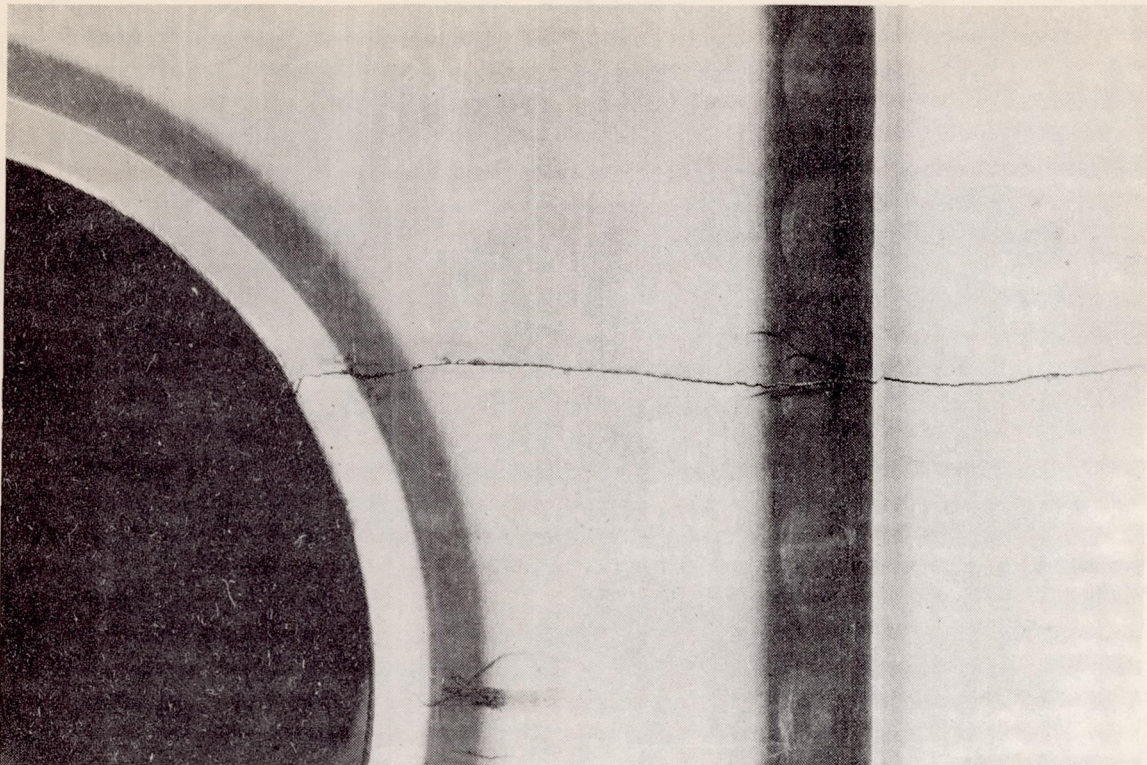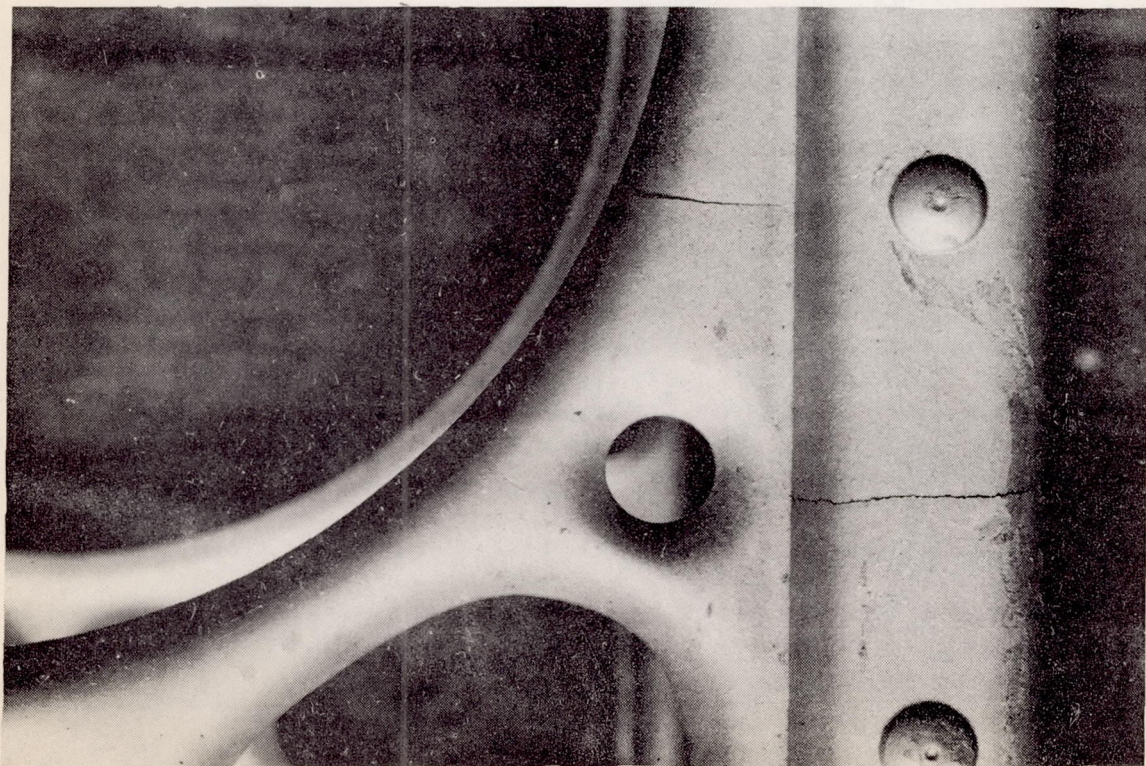Figure 8.- Detail of perforation and origin of first
cracks in N.A.F. girder No. 6351-2

Fig. 8

Figure 9.

Figure 10.

Figure 11.

Figure 12.